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DIFFERENTIAL GPS FOR AIR TRANSPORT - STATUS

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OUTLINE

BACKGROUND

- **Global Navigation Satellite System (GNSS)**
- **Initial Operational Capability for Various Transport Aircraft Operations**
- **Differential GPS**

LARC/HONEYWELL FLIGHT TESTS

- **Description of System and Tests**
- **Test Results**

OHIO UNIVERSITY GRANT

- **GPS Interferometry**
- **Attitude & Heading Determination**
- **Precision DGPS Navigation**
- **Status**

Aerospace Guidance &
AGCB Controls Branch

The presentation presents background on what the Global Navigation Satellite System (GNSS) is, desired target dates for initial GNSS capabilities for aircraft operations, and a description of differential GPS (Global Positioning System).

The presentation also presents an overview of joint flight tests conducted by LaRC and Honeywell on an integrated differential GPS/inertial reference unit (IRU) navigation system. The overview describes the the system tested and the results of the the flight tests.

The last item presented is an overview of a current grant with Ohio University from LaRC which has the goal of developing a precision DGPS navigation system based on interferometry techniques. The fundamentals of GPS interferometry are presented and its application to determine attitude and heading and precision positioning are shown. The presentation concludes with the current status of the grant.

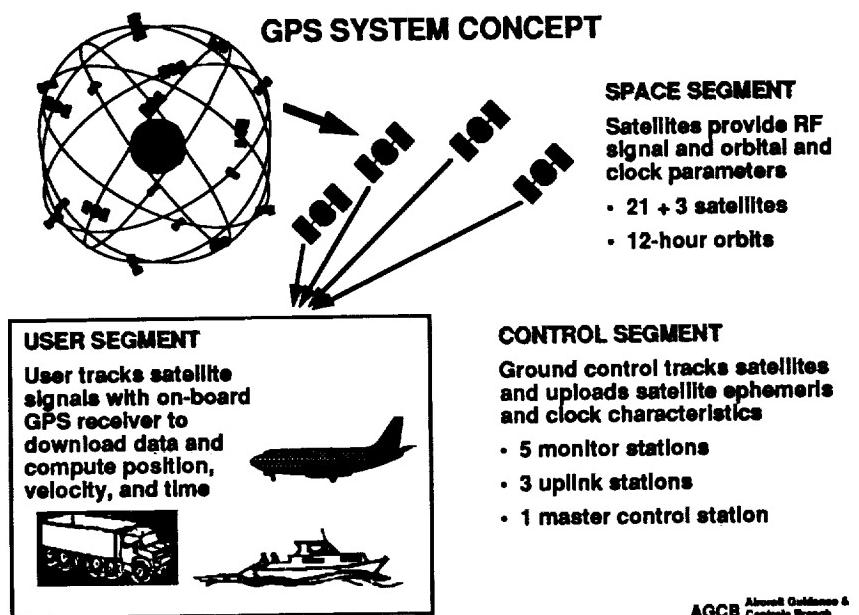
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GNSS (GLOBAL NAVIGATION SATELLITE SYSTEM)

- **GNSS, Defined by ICAO, Encompasses All Current and Future Satellites that will be Available for Global Aircraft Navigation**
- **Currently, Navstar GPS and GLONASS are Providing Global Navigation Signals in a Pre-Operational Mode**
- **The GPS (Global Positioning System) is Scheduled to be Operational Late '93 or Early '94 and GLONASS '95 (?)**
- **Expect in the Future that GPS like Signals will be Available on Geostationary Inmarsat Satellites**

AGCB Aircraft Guidance & Control Branch

The Global Navigation Satellite System (GNSS) is the name adopted for world-wide satellite navigation by the International Civil Aviation Organization (ICAO). Two global satellite navigation systems are currently under development and both are currently providing signals for use in a pre-operational mode. One is the Global Positioning System (GPS) being developed in the United States by the DOD and the other is the Global Orbiting Navigation Satellite System (GLONASS) being developed by Commonwealth of Independent States (CIS and formerly the Soviet Union). The GPS is expected to achieve full operational capability by late 1993 or early 1994 and GLONASS in 1995. Substantial uncertainty exists for the operational date of GLONASS due to the current instability in the CIS. Plans are underway to provide GPS-like signals on the geostationary Inmarsat satellites. These signals will provide redundant coverage for increased reliability. In addition, Inmarsat is being considered for transmission of a health/status message for GPS called the GPS Integrity Channel (GIC). In summary, GNSS encompasses all satellite systems providing navigation information including integrity messages regarding the navigation information.

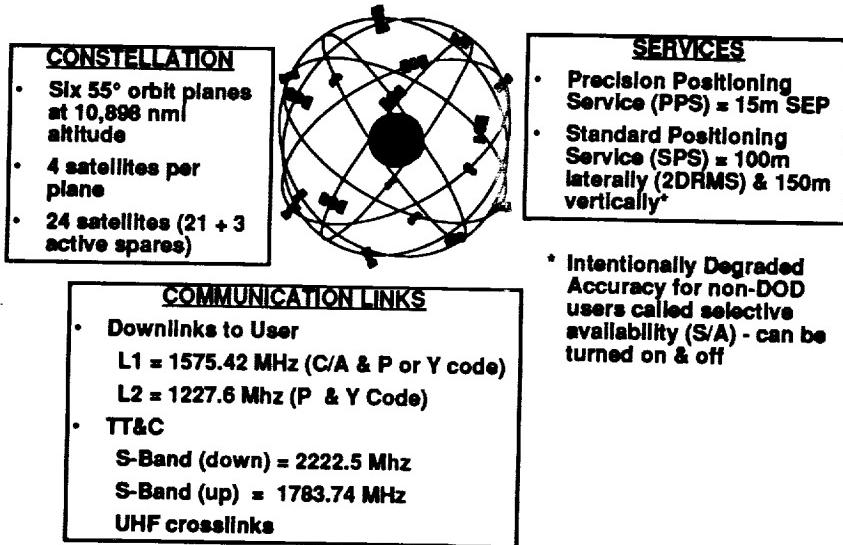


There are three major segments for a global satellite navigation system – the space segment, the user segment, and the control segment. This viewgraph depicts these segments and gives some general information about them for the GPS. The GPS space segment will contain 24 satellites – 21 will be active and 3 will be spares to replace a malfunctioning or failed satellite. The space segment provides an RF signal which contains orbital and precision clock parameters for the satellite. The RF signal is also modulated by a unique digital bit-pattern sequence or code.

The user segment consists of those entities (airplanes, ships, trains, cars, trucks, boats, surveyors) which have a GPS receiver. The GPS receiver also contains a precision clock and generates the same unique bit patterns as the satellites. The receiver downloads the orbital data and clock parameters of the satellite and correlates the received bit pattern with the receiver bit pattern to determine signal transmission time. Given this time, the range (commonly referred to as the pseudorange) to the satellite is computed using the speed of light and compensation for ionospheric and tropospheric bending. From four pseudoranges the three-dimensional position of the vehicle is determined given the satellite positions (determined from transmitted orbital parameters). Four pseudoranges are required because there are four unknowns (3 position dimensions and the receiver clock bias). The receiver also computes the vehicle velocity from Doppler measurements and provides a precision time measurement.

The control segment tracks the satellites. From tracking measurements the control segment computes the ephemeris and clock parameters of each satellite and then uploads this data to the satellites. The GPS has 5 monitor stations, 3 uplink stations, one master control station, and one backup control station.

GPS BLOCK II SATELLITES



AGCB Advanced Guidance & Control Board

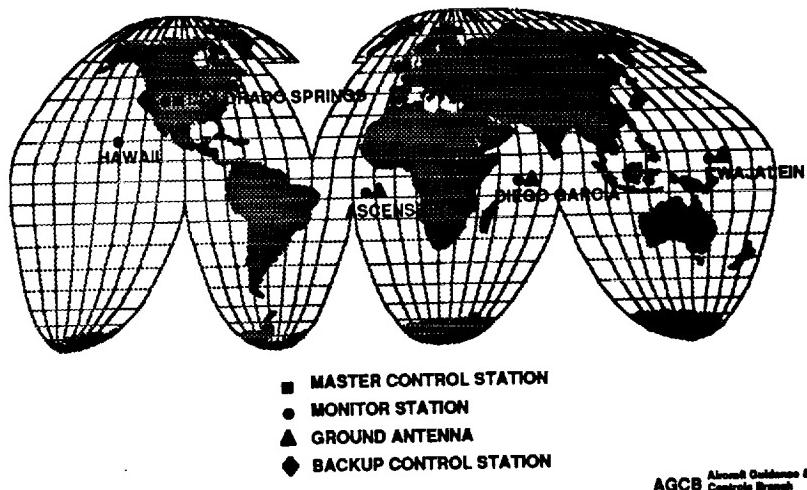
The GPS satellites will be contained in six 55° orbital planes 10,898 nautical miles above the earth which results in 12-hour orbits. Four satellites will be in each plane for a total of 24 satellites. Twenty-one of the satellites will be active and 3 will be spares for use in the advent of a satellite malfunction or failure.

The GPS provides two types of services. One is Precise Positioning Service (PPS) and the other is Standard Positioning Service (SPS). PPS is intended primarily for DOD or military operations while SPS is provided for civilian operations. The accuracy of the PPS is 15 meters SEP (spherical error precision – probability of errors within specification is 50%). This accuracy is met with a GPS receiver that acquires a satellite signal with the carrier-modulated Course Acquisition (C/A) code and then subsequently locks onto the carrier-modulated precision (P) code which provides higher accuracy than the C/A code.

SPS is intended for civilian use and civilian receivers use the C/A code. The 2DRMS (twice the standard deviation of the circular standard error – probably of errors within specification is 96%) accuracy of this service is 100 meters horizontally and 150 meters vertically. The SPS accuracy results from an intentional degradation of the signal by the DOD which is referred to as Selective Availability (S/A). S/A can be turned on and off. When off the SPS accuracy would be on the order of 30 meters.

There are two communication downlinks to the user called L1 and L2. L1 operates at 1575.42 MHz and carries both C/A and P code plus system data. The DOD can encrypt the P code and when so done the P code is referred to as Y code. A key must be obtained from the DOD to decipher the encrypted code. L2 operates at a frequency of 1227.6 MHz and carries P or Y code plus system data. Tracking, telemetry, and control (TT&C) uses two S-band frequencies – 2222.5 MHz for downlink and 1783.74 MHz for uplink. TT&C also makes use of UHF crosslinks.

GPS CONTROL SEGMENT



This viewgraph shows the location of the various ground stations and equipment for the GPS Control Segment. The master control station is located in Colorado Springs with a backup control station located in California. Monitor stations are located in Hawaii, Ascension Island, Diego Garcia, and Kwajalein.

GNSS INITIAL OPERATIONAL CAPABILITY TARGETS (NAVIGATION)

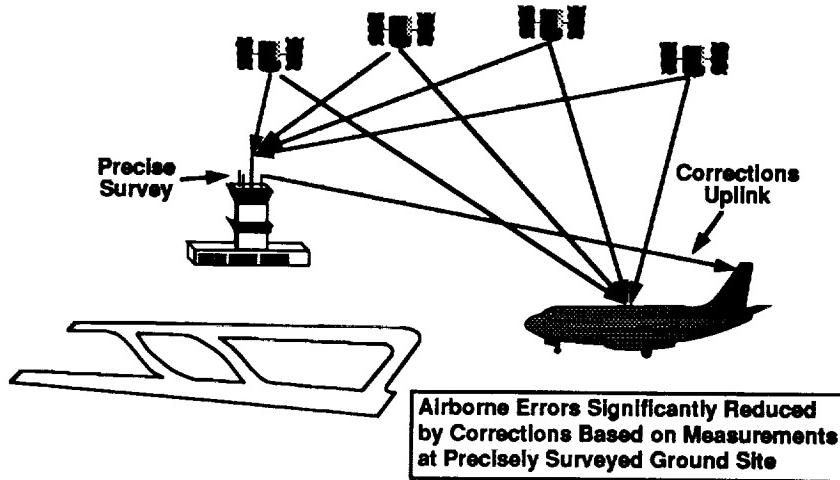
YEAR	<u>Initial Operational Capability</u>
93	GNSS Supplemental Means (Oceanic)
94	GNSS Sole Means (Oceanic)
94	GNSS Airport Surface Navigation <small>(Requires augmentation; e.g., Differential GNSS & Low Speed Data Link)</small>
95	GNSS Precision Approach (200 DH / 1800 RVR) <small>(Requires augmentation; e.g., Differential GNSS & Low Speed Data Link)</small>
95	GNSS Sole Means (Domestic)
97	GNSS-Based Autoland & Takeoff (300 RVR) <small>(Requires augmentation; e.g., Differential GNSS & Low Speed Data Link)</small>

AGCB Aircraft Guidance &
Control Branch

A GNSS task force under the direction of the RTCA was requested by the Federal Aviation Administration (FAA) to examine various applications of GNSS and to develop a series of basic technical system requirements to achieve various desired capabilities for early implementation of GNSS within the United States. The dates listed were obtained from the recently released task force report and are the earliest desired initial operational capabilities (IOC) for GPS. The GNSS Task Force believes that the technology will be in place to realize the initial operational capabilities by the dates shown. These capabilities would initially be approved by the FAA for certain areas and for use by properly equipped aircraft.

The GNSS Supplemental Means IOC is expected to occur this year. The definition of Supplemental Means navigation is the use of GPS in conjunction with some other navigation system such as Omega. Sole Means navigation is GPS navigation only without the availability of another on-board navigation system.

DIFFERENTIAL GPS



This viewgraph depicts the basic concept of differential GPS. The basic concept is to improve the airborne navigation solution by transmitting corrections to the airborne system based on GPS measurements made at a fixed site whose position is precisely known. The fixed ground site makes measurements of the satellites in view and computes corrections to the measurements based on its known location. These corrections are then transmitted to the airborne system (or ship, train, etc.) and processed in the airborne system to reduce the errors in the airborne measurements.

HONEYWELL/LARC DGPS/INS FLIGHT TESTS

- **Objectives of Tests were**
 - **Determine Potential of DGPS/INS for Use in Autoland Systems of Space Vehicles.**
 - **Record Extensive Data Base for Post-Flight Nav Accuracy Assessment**
- **Flight Tests Conducted Using HW Integrated DGPS/INS System (2-channel C/A code tracking GPS receiver)**
- **Data Gathered During Joint Flight Test Conducted by LaRC & HW Oct-Nov 1990 (S/A Off)**
- **Recorded DGPS/INS, MLS/INS, Autonomous GPS, Inertial Nav Data on Aircraft; Laser Tracking Position on the Ground**

AOCB Aerospace Guidance & Control Branch

In early 1990, LaRC and Honeywell entered into an agreement to flight test an integrated DGPS/Inertial Navigation System (INS) on Langley's Transport Systems Research Vehicle (TSRV) - a Boeing 737 research aircraft. The DGPS/INS had been developed by Honeywell. The system consisted of a GPS receiver, a GPS processor, and a laser gyro inertial reference unit.

One objective of the test was to determine the potential of the DGPS/INS for use in autoland systems for space return vehicles - e.g. the shuttle and emergency return vehicle vehicles from the space station. A second objective was to record an extensive data base for post-flight evaluations and assessment of the navigation accuracy of the DGPS/INS.

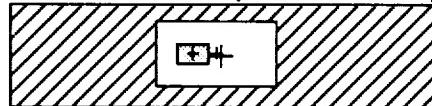
The GPS receiver used in the Honeywell system was an early receiver design. The receiver was a 2-channel sequential C/A code tracking receiver. The technology has advanced rapidly making this design outdated. Typical receiver designs today have 6 to 10 channels and some have 12 channels for simultaneous tracking of several satellites.

The flight tests were conducted in October and November of 1990 during a time when the Selective/Availability (S/A) was turned off, that is, the intentional DOD corruption was not being added to the transmitted signals. The DOD had turned S/A off so that they could obtain good accuracy with the civilian GPS receivers they were using for their Desert Storm operations. There were not enough military GPS receivers available for their planned operations at that time. In any case, the navigation accuracy of the DGPS/INS should be the same even if S/A was on since differential GPS removes the corruption added by S/A.

The data that was recorded simultaneously on the TSRV for these tests included data from the DGPS/INS, a Microwave Landing System (MLS)/INS, Autonomous GPS (the basic measurements from the GPS receiver without inertial aiding), and aircraft inertial and air-data measurements. On the ground, the TSRV position was measured by a laser tracking and recorded along with a time tag for post-flight merging with the aircraft data.

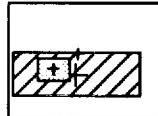
NAV ERRORS VS LANDING SYSTEM REQUIREMENTS

Cat I – 200 Ft DH (112.2 x 27.2 Ft)



Cat II – 100 Ft DH (33.8 x 11.4 Ft)

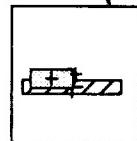
20 Ft



Key

	- ICAO ILS Reqmt
	- MLS/INS
	- DGPS/INS with Rad Alt

Cat III – 50 Ft DH (26.4 x 3.6 Ft)



Box Dimensions
are ± 2 sigma
about mean

AGCB Aircrew Guidance &
Control Branch 10

This viewgraph shows the results of a statistical analysis on the flight test data which was presented at the Institute of Navigation Conference in January 1992 and published in an ION paper by R. M. Hueschen and C. R. Spitzer of LaRC.

The cross-hatched boxes represent the performance windows established by the International Civil Aviation Organization (ICAO) for Category I, II, and III Instrument Landing Systems (ILS). The windows are centered about the ILS localizer and glideslope landing path (large plus signs) at specified decision heights. The width and height of the boxes represent, respectively, the required lateral and vertical performance. The top cross-hatched box is the required system performance an ILS system must meet to be certified for Category I operations. Data must show that the aircraft will be inside this box 95% of the time (statistically two standard deviations or 2σ) at 200 feet decision height. The middle cross-hatched box is the 2σ performance box for Category II performance at 100 feet decision height and the bottom one for Category III performance at 50 feet decision height.

The shaded boxes show the 2σ performance obtained from the MLS/INS. These boxes show that the MLS/INS met Category I, II, and III performance relative to the localizer (lateral deviation) and Category I and II performance relative to the glideslope (vertical deviation). The plus signs inside the boxes represent the mean of the lateral and vertical deviation, respectively, from the localizer and glideslope centerlines.

The white boxes represent the 2σ performance of the DGPS/INS with radar altimeter aiding. These boxes show that the DGPS/INS with radar altimeter aiding met the Category I performance requirement. This system was close to meeting the Category II lateral performance requirement and considerably exceeded the Category II and III vertical performance requirement. The vertical accuracy of DPGS/INS without radar altimeter aiding could not meet the Category I performance requirement.

OHIO UNIVERSITY GRANT

Three-Year Grant (initiated April 6, 1992) from LaRC to Developed GPS Interferometry Technology

Year 1

Demonstrate GPS Interferometry to Achieve Real-Time, 3-D Relative Positioning Accuracies to 0.1 meter

Investigate Feasibility of GPS Interferometry for In-Flight Reference System and Autoland Applications

Year 2

Continued Development of GPS Interferometry Core Technology

Improvement of Aircraft Attitude and Heading Determination from 1 mrad to 0.1 mrad

Year 3

Full Characterization of GPS Interferometry In Terms of Accuracy and Robustness

Integration of GPS with Inertial Measurement Data

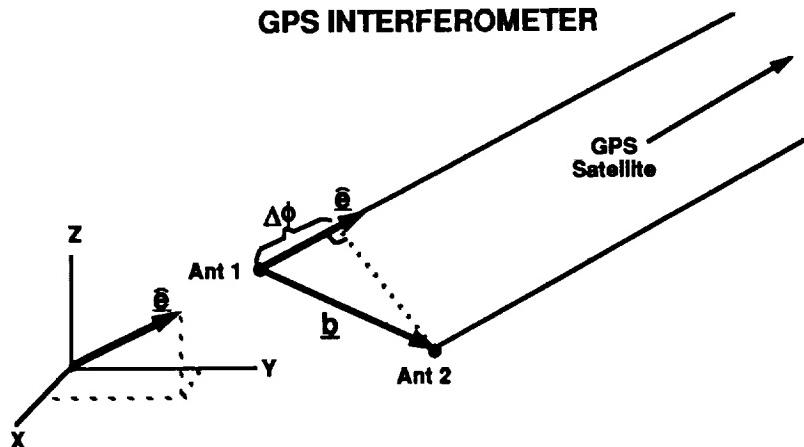
AQCB Aerospace Guidance & Control Branch

A three-year grant (renewable on a yearly basis) was initiated with Ohio University on April 6, 1992 to develop GPS interferometry technology. A major purpose of the grant is to develop a differential GPS airborne in-flight reference system for the TSRV. In addition to serving as an in-flight reference system, this system is planned to be coupled to research guidance and control systems designed for GPS navigation in future flight tests.

The focus of the first year of the grant was to implement and flight test a DGPS navigation system using based on GPS interferometry techniques and demonstrate that the system could achieve real-time three-dimensional relative positioning accuracy of 0.1 meter. Also, this implementation was to determine the feasibility of using the system as an in-flight navigation reference and for autoland applications. As an in-flight reference system, it would be used to determine the performance of other research navigation systems such as a low-cost GPS or a GPS/low-cost IRU system. The feasibility for autoland applications is to be determined by assessing the performance of the inertially-aided TSRV autoland system when coupled to the DGPS during the flight tests.

The focus of the second year was continued development of the core GPS interferometry technology (e.g. developing algorithms to resolve carrier-phase integer ambiguity and developing methods to minimize multipath). During this year, the grant will continue some previous research by Ohio University on aircraft attitude and heading determination with GPS interferometry. The goal is to improve attitude and heading accuracy from previously demonstrated accuracy of 1 mrad to an accuracy of 0.1 mrad.

In year three the grant would complete the full characterization of GPS interferometry in terms of the system robustness and accuracy achievable under various conditions. Also, the grant would address the integration of the GPS data with inertial measurements focusing primarily on low-cost inertial systems.

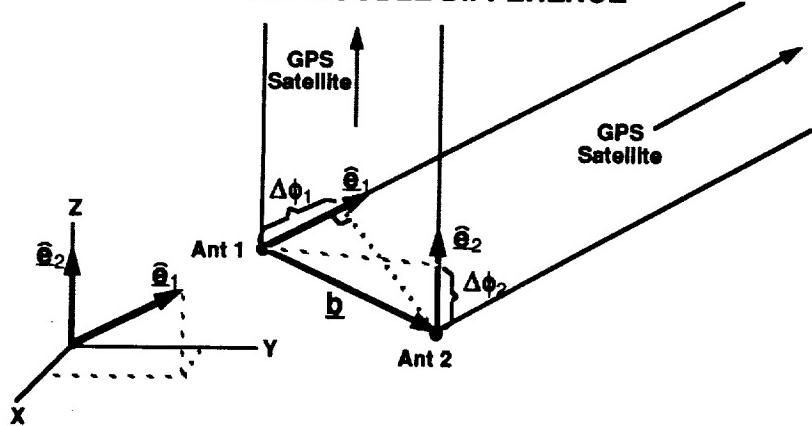


$$\Delta\phi = \phi_1 - \phi_2 = \mathbf{b} \cdot \hat{\mathbf{e}} + N\lambda + f\Delta t_{ue}$$

AGCB Aerospace Guidance &
Control Branch 12

This viewgraph illustrates the fundamentals of GPS interferometry. A GPS interferometer consists of two GPS antennas separated by a baseline vector, \mathbf{b} , and connected to a GPS receiver. Each antenna receives signals from the same GPS satellite and the paths to the satellite from the antennas are considered parallel given the relatively short length of \mathbf{b} compared to the distance to the satellite (approximately 11,000 nautical miles). In other words, the GPS carrier signal can be considered as a plane wave. The direction to the satellite is represented by the unit vector, $\hat{\mathbf{e}}$. The phase of the GPS carrier signal is measured at each antenna resulting in phase measurements ϕ_1 and ϕ_2 . Taking the difference of these measurements, called the single difference, represents the path length difference of the paths from the satellite to each antenna and is given by $\Delta\phi$ which is equal to the dot product of the baseline vector with the unit vector plus two additional terms. The term $N\lambda$ is a distance equal to the ambiguity in the number (N) of whole carrier cycles and is referred to as integer ambiguity. The term $f\Delta t_{ue}$ is a distance error due to an unknown receiver clock offset from the satellite clock.

THE DOUBLE DIFFERENCE



$$DD = \Delta\phi_1 - \Delta\phi_2 = b \cdot (\hat{e}_1 - \hat{e}_2) + N\lambda$$

AGCE Aircraft Guidance &
Control Branch 13

If another single difference is determined from two more phase measurements from the carrier signal of another satellite, then taking the difference of two single differences forms the double difference (DD). The double difference eliminates the error due to receiver clock offset. However, the double difference will still contain an error due to carrier cycle integer ambiguity.

BASELINE DETERMINATION

- Two Antennas
- Four Satellites
- Three Double Differences

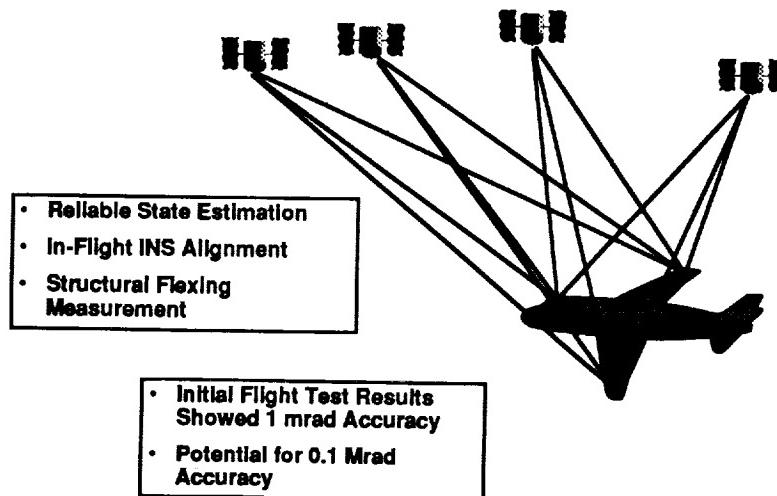
$$\begin{bmatrix} \mathbf{DD}_1 \\ \mathbf{DD}_2 \\ \mathbf{DD}_3 \end{bmatrix} = \begin{bmatrix} (\hat{\mathbf{e}}_1 - \hat{\mathbf{e}}_2)^T \\ (\hat{\mathbf{e}}_1 - \hat{\mathbf{e}}_3)^T \\ (\hat{\mathbf{e}}_1 - \hat{\mathbf{e}}_4)^T \end{bmatrix} \begin{bmatrix} \mathbf{b}_1 \\ \mathbf{b}_2 \\ \mathbf{b}_3 \end{bmatrix} + \begin{bmatrix} \mathbf{N}_1 \\ \mathbf{N}_2 \\ \mathbf{N}_3 \end{bmatrix} \lambda$$

Double differences Baseline Vector
 ↑ ↑
 Unit Vectors to Satellites Integer Ambiguities

AGCB Aerospace Guidance &
 Control Branch 14

Given two GPS antennas and four GPS satellite carrier signals, three independent double differences (DD) can be formed. The three double differences can be put into vector form as shown in the equation on the viewgraph. The baseline vector between the two antennas can be determined by solving this equation. This solution will contain the error due to carrier cycle integer ambiguity represented by the term on the right until the ambiguity can be resolved. In general, search methods can be used to quickly resolve the integer ambiguities when more than four satellites are available. Since the L1 carrier wave length is 19 cm and highly accurate phase measurements can be made in the GPS receiver, the baseline vector vector can be determined with high precision, especially when the carrier cycle integer ambiguity can be resolved. With the technology available in today's GPS receivers, the integer ambiguity is on the order of 5 cycles (approximately 1 meter) in the initial solution of the baseline vector. The time to resolve the integer ambiguity with current methods depends on the number of satellites available. A minimum of five satellites is required to resolved the integer ambiguity (four are required to obtain a three-dimensional solution). With five satellites available and current algorithms, the time to resolve the ambiguity can be on the order of 100 to 200 seconds. If six satellites are available, the time is less than 100 seconds. These times are based on the speed of a Intel 486 processor.

ATTITUDE AND HEADING DETERMINATION

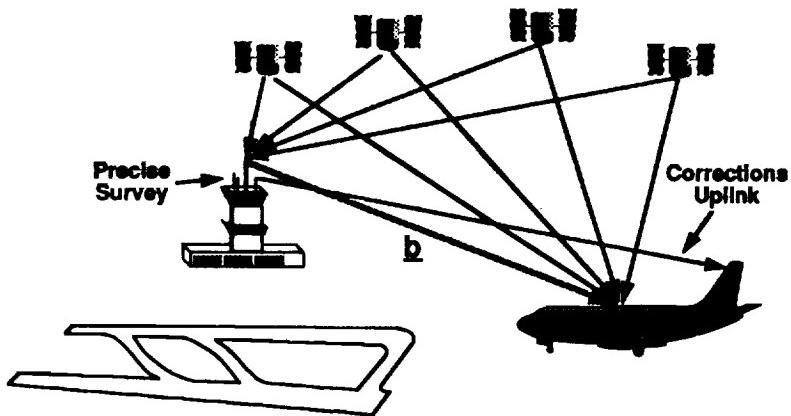


AGCB Aeronautics & Controls Branch 15

If multiple antennas are installed on an aircraft and the distance between them is measured accurately, then GPS interferometry can be used to precisely determine aircraft attitude and heading. The GPS attitude and heading determination could be used in conjunction with an inertial reference unit (IRU) to provide reliable state estimation. It could also be used to align an inertial navigation system (INS) in flight (INS alignment normally requires 10 to 20 minutes sitting on the ground). The potential exists to determine aircraft structural flexing with the multiple antenna installation in conjunction with an IRU.

A GPS attitude and heading system was flight tested by Ohio University on their research DC-3 and the flight test results showed an accuracy of 1 mrad for attitude and heading determination. The heading accuracy is generally better than that obtained by IRU's. With further development, there is the potential to increase the accuracy of GPS attitude and heading determination to 0.1 mrad.

PRECISION DGPS NAVIGATION



Determine Baseline b to within 0.1m in Real Time

Aircrew Guidance &
AGCB Control Branch

GPS interferometry can be used for precise position determination employing differential GPS (DGPS) techniques. For DGPS operation, one GPS antenna and receiver are located on the ground. This antenna is mounted at a precisely surveyed point. Another antenna and receiver are placed on the aircraft. The ground site then makes measurements on the GPS signals and determines corrections for the received signals based on its precisely known location. These corrections are then transmitted (uplinked) to the aircraft and applied to the GPS signals measured by the airborne receiver. Using the current computer technology, these corrections can be processed with the GPS receiver measurements and interferometry calculations to determine the baseline vector (the vector from the GPS ground antenna to the airborne GPS antenna) in real-time. The potential accuracy in the determination of the baseline vector is 0.1 meter. Achieving this accuracy is dependent on the success of developing robust processing techniques to minimize integer ambiguity and multipath errors. The minimization of multipath will also be dependent on hardware considerations such as ground and airborne antenna design and ground antenna siting.

PRECISION DGPS NAVIGATION STATUS

- **Flight Tests on ATOPS TSRV (B737) Planned for Mid-April 1993 at Wallops Flight Facility**
 - Open-Loop
 - Closed-Loop Autoland
- **Potential Flight Test on TSRV at PAX River in Mid-May 1993**
 - Different Environment for System Test
 - Process "Truth" Position Using Simultaneous Measurements from Multiple Trackers

AGCS Aircraft Guidance & Control Branch 17

This viewgraph presents the status of the first-year effort of the grant with Ohio University. A DGPS navigation system has been developed and is planned to be flight tested on the TSRV in April 1993. The initial flight tests will consist of open-loop (not coupled to automatic G&C) approaches and landings to runways at Wallops Flight Facility. While performing these tests the aircraft will be tracked by a laser tracker at Wallops and the tracking will be recorded for post-flight processing with the airborne recorded data. After analyses show that the navigation system is performing properly and with acceptable accuracy, the system will be coupled to the autoland system of the TSRV and closed-loop approaches and landings will be performed (approximately forty are planned).

Potential flight tests are also planned at the Naval Air Warfare Center (NAWC) facilities at Patuxent River, Maryland. These tests will provide another environment in which to test the performance of the DGPS navigation system. Also, the NAWC will track the TSRV with multiple tracking facilities. NAWC will use the multiple tracking data and airborne navigation data to develop post-flight processing algorithms that are intended to provide a highly accurate position-reference determination. This post-flight processed tracking data will also be provided to LaRC for our own DGPS navigation system performance analyses.